Single-event keV proton detection using a delta-doped charge-coupled device

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Using a delta-doped charge-coupled device (CCD), we have demonstrated an order-of-magnitude improvement in the low-energy cutoff for particle detection compared to conventional solid-state detectors. Individual protons with energies in the 1.2-12 keV range were successfully detected using a delta-doped, back-illuminated CCD. Moreover, it is shown that, by measuring the charge generated by the proton, it is potentially possible to use delta-doped CCDs to determine the energy of the incoming particle.

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For imaging energetic particles, solid state silicon particle detectors are an attractive alternative to conventional methods using microchannel plates. Compared to microchannel plates, solid state detectors are compact, robust, and relatively inexpensive, with high resolution and low power consumption. In addition, because they produce a signal proportional to the incident particle energy, solid state detectors can provide energy resolution of individual particles as well as incidence rate and position information.

Conventional silicon detectors and imagers, however, perform poorly at low particle energies. Back-illuminated silicon CCDs with untreated surfaces have a dead layer produced by a potential well which is the result of band-bending due to the accumulation of charge in the silicon/native oxide interface. Other detectors such as strip detectors also have a dead layer created by undepleted surface electrode. Since the detector is not sensitive to carriers generated in the dead layer, ionization radiation which has insufficient energy to penetrate beyond the dead layer produces no detectable charge. Therefore, the thickness of the dead layer determines the low-energy cut-off for silicon detectors. Traditionally, untreated CCDs are not used for particle detection; for conventional silicon strip detectors, the low-energy cutoff for protons can be on the order of 100 keV.

Reducing the low energy threshold of silicon detectors requires reducing the thickness of the dead layer. This can be done either by reducing the depth of the surface potential well, or by reducing the thickness of the surface electrode, as appropriate to the device in question. There have been attempts to modify the surface potential using high-work-function metals or applied voltages, with various degrees of success. Shallow ion implantation has been used with more success in CCDs, strip detectors and diode arrays. Commercially available detectors using shallow ion implantation list a ~10 keV detectability threshold for protons [1]. Other groups have also achieved some success detecting low energy particles using detectors capped with ultrathin oxides [2-5]

In this paper, we report measurements with a delta-doped CCD that demonstrate an extension of the detectable energy range for protons by an order of magnitude over shallow ion-implanted solid state detectors.

A technique has been developed at Jet Propulsion Laboratory's Microdevices Laboratory using silicon molecular beam epitaxy (MBE) to grow a delta-doped epitaxial silicon layer on the exposed (unprocessed) back surface of a fully-processed detector [6]. In this approach, MBE has been used to grow an additional 1.5 nm of single-crystal silicon on the backside of the detector, while incorporating a sheet of 2×10^{14} boron/cm^2 atoms (nominally in a single monolayer of the crystal) approximately 0.5 nm from the silicon/silicon native oxide interface. The resulting delta-doped detector is then sensitive to ionizing radiation with a penetration depth greater than ~0.5 nm. Because this is a back-illuminated device, particles enter the silicon back surface and generate secondary electron-hole pairs very near the back surface. The carriers generated by the incoming particle diffuse across the field-free region of the device before arriving at the frontside potential well where they are collected and serially read out. Delta-doped CCDs exhibit 100% internal quantum efficiency throughout the UV region of the spectrum, even when much of the absorption occurs within a few nm of the surface. In previous papers, Nikzad *et al.*, and Smith *et al.* [7,8] reported the use of a delta-doped CCD for detection of low-energy electrons (with few nanometers of penetration depth into silicon), demonstrating that electrons could be detected at energies more than an order of magnitude lower than the lowest previously reported measurements [9-12]. The quantum efficiency measurements were, however, somewhat complicated due to backscattering of electrons. To address this issue, single-event protons are used in the measurements presented in this paper.

A fully-processed EG&G Reticon 512 x 512 pixel CCD with 27-μm square pixels was thinned and delta-doped for these experiments. The details of modification of the CCD using molecular beam epitaxy have been described elsewhere [13]. The experiments were performed in a high-vacuum chamber with a special CCD camera (with the optics removed so that the surface of the CCD is exposed) mounted inside the chamber. To reduce the dark current, the CCD was cooled using liquid nitrogen to approximately -30°C, where the integrated dark current was insignificant. A hot cathode source is used to ionize hydrogen gas, and the resulting ions are accelerated by an electric field. An electromagnet bends the proton beam at right angles to the source, where it enters the main chamber. The proton beam was set for a particular energy, and the current into the electromagnet was adjusted until the beam was directed onto the CCD camera assembly. A mechanical shutter was used in front of the CCD to control the exposure time of the CCD to the incident proton beam. Signal from the CCD was read out and the resulting data was stored in a computer.

The proton flux was sufficiently low that single protons were incident on less than 10% of the pixels in the array with the majority of the pixels receiving no protons. Only a few pixels were hit by more than one proton. In this arrangement, there is a direct correlation between the beam energy and the charge in a hit pixel. However, several factors complicate this correlation. Because of the design of the device, these CCDs are thinned to approximately 15 μm of field-free region. Carriers generated near the back surface of the device will diffuse to the frontside potential well, where they will be collected. This field-free region is a significant fraction of the 27 μm pixel size and therefore, charge can be divided among several pixels. However, all observed charge within our noise limit was contained in approximately a 3 x 3 pixel area. In the analysis, the charge in this area was summed and was assigned to a single proton. A small amount of background was present due to dark current, signal generated from light leak into the vacuum chamber, and the ionizer filament. This background was measured and was subtracted from the signal. For each incident proton energy, a histogram was created of the charge from each hit, and the mean and standard deviation of charge versus energy was calculated. This is plotted in Fig. 1. There are three major features to discuss in figure 2: the low-energy cutoff of the detector, the linearly increasing response of the detector with proton energy, and the quantum yield (or the number of electron-holes generated) at this energy range.

Figure 1 indicates that it is possible to detect protons with energies as low as 1.25 keV. We have used TRIM™ (Transport of Ions in Matter) code to estimate the range of energetic protons in silicon which is shown in figure 2. Based on these calculations, a 1 keV proton has a maximum penetration range of 300 Å in silicon. This is well within the dead layer (~1 μm) of a silicon detector with no treatment. Indeed, without any treatment of the silicon detector surface, the detectable energy threshold will be in the 50-100 keV range since, for example, protons with 50 keV of energy only penetrate approximately 0.5 μm into silicon. With ion-implantation treatment, conventional silicon detectors exhibit a low-energy cutoff of 8 to 10 keV, nearly an order of magnitude more limited than delta-doped CCDs. The source capabilities excluded beam production below 1 keV for the measurements presented in this paper. However, this cut-off could also be limited by the noise floor of the particular CCD used in these experiments. Using a CCD with better noise performance, it may be possible to reduce the low energy cut-off even further.

It can be seen in figure 1 that the number of electrons produced by incident protons appears to be a linearly increasing function of incident proton energy, as expected. An energetic particle passing through silicon generates a number of electron-hole pairs which is proportional to the energy lost in the silicon. By collecting and measuring this charge, the silicon detector can provide energy-resolved detection of particles. The constant of proportionality (or quantum yield) [14,15] measured here differs from that for x rays and high-energy particle detection (i.e., approximately 3.65 eV of energy to generate one electron-hole pair or ~277 electrons per keV of incident energy). Fig. 1 indicates a yield of approximately 69 electrons per keV of incident energy, differing from the high-energy value by a factor of 4. Several effects may be contributing to the difference between the measured yield and the calculated value based on one electron per 3.65 eV of incident energy. Generally speaking, this observed difference is caused by either a change in the rate of charge generation at these lower energies, or the charge is being produced at a higher rate but only a fraction of it is being collected before recombination. Delta-doped CCDs have been measured to have nearly 100% internal quantum efficiency in the UV, indicating that all photo-generated electrons (or particle-generated electrons) should be collected in this CCD. The field-free region in these CCDs, however, can contribute to lateral diffusion of generated electrons, so some fraction of the energy generated by low-energy particles may be collected (or recombined) more than one pixel-length away from the point of origin. At these low incident energies, most of the interactions occur near the surface, so that it is possible that a significant fraction of the incident energy is not deposited in the crystal (as opposed to high-energy particles or x rays that deposit most of their energy deep in the lattice). Measurements using delta-doped devices that have lower noise values and can be depleted could help in the understanding of this phenomenon.

One possible application of these detectors is energy-resolved particle detection. Maps of the average array response of a delta-doped CCD to protons of 1.75 keV and 12 keV energy are shown in figure 3a and 3b respectively. While the response to 12 keV protons is promising for the measurement of the energy of incoming particles, the distribution for 1.75 keV protons is too broad. Further investigation is underway and details of this analysis will be presented in a separate publication. The noise floor of the detector, the thickness of the field-free region in the device, and the increased probability of inelastic scattering for protons with lower incident energy, could be contributing factors to the shape of the response.

In conclusion, a delta-doped CCD has been used to demonstrate the reduction of the dead layer in a silicon detector to approximately 1 nm. This has been shown by reducing the minimum detectable proton energy to at least 1.2 keV, with an energy resolution of about 1.5 keV. Furthermore, it has been shown that it is potentially possible to perform energy-resolved detection of protons in the 1.2 to 10 keV range. However, the quantum yield of these measurements are not fully understood at this time. Work is underway for further improvement in the noise performance and energy resolution and understanding the minimum detectable energy and the quantum yield.

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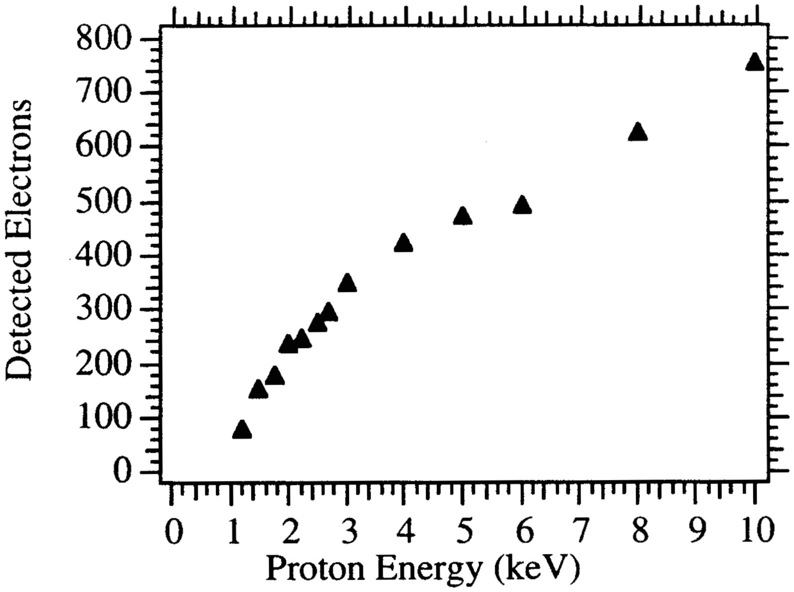
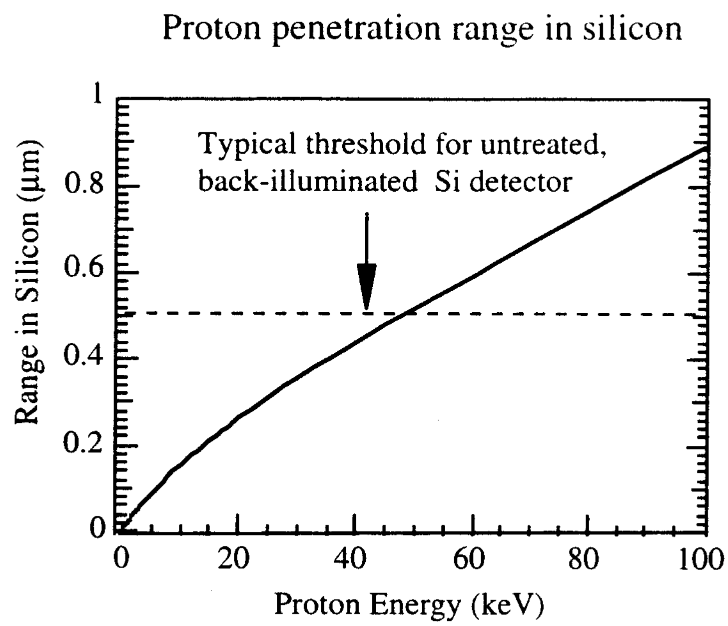
Figure 1: The charge collected per proton hit vs. incident proton energy. The detected signal (number of electrons) increases with the increasing energy of the incident proton.

Figure 2: Solid line is the TRIM calculations of range of energetic protons in silicon vs. the incident proton energy. The dashed line represents the approximate extension of the dead layer for an untreated silicon detector. At 50 keV the range in silicon in less than 1μm which is approximately the width of the dead layer.

Figure 3 The response of the delta-doped CCD to protons at a) 1.75 keV and b) 12 keV where horizontal plane depicts the array and the vertical axis indicates the measured signal per pixel. At 1.75 keV, the distribution is broader than 12 keV, partially because of the noise floor of the detector. The vertical axis in both figures are arbitrary units. Note that because of different amplification in the two measurement, the noise floor and scales are different in the plots.



Nikzad et. al., Figure 1 of 3b



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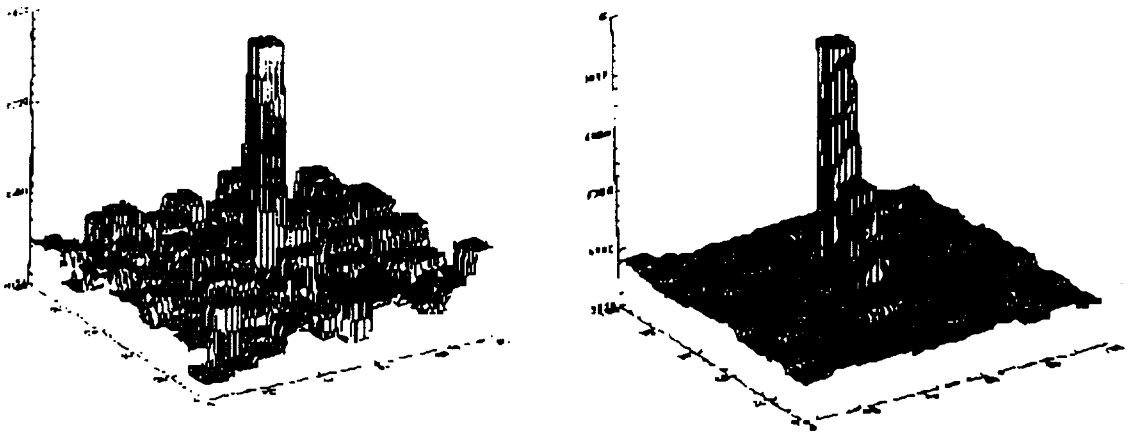

a

b

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